Realtime raytracing of Electron Cyclotron waves for Neoclassical Tearing Modes control in the Divertor Tokamak Test facility

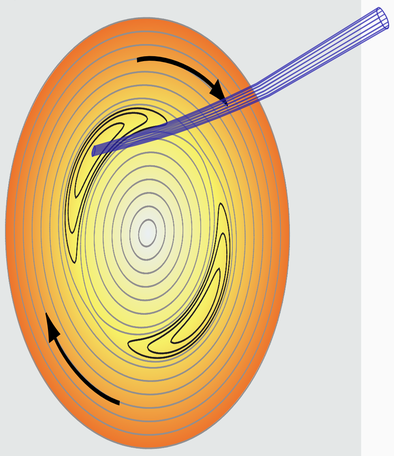
[1]M. Guerini Rocco† [2]D. Farina [2]A. Mariani [2]Natale Rispoli [23]G. Granucci [2]L. Figini

[1]Department of Physics, University of Milano-Bicocca, Milan, 20126, Italy
[2]Institute for Plasma Science and Technology, National Research Council, Milan, 20125, Italy
[3]DTT S.C.a r.l., Frascati, Italy

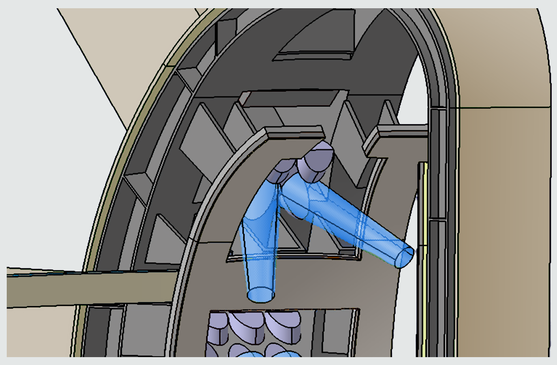
Introduction

Neoclassical Tearing Modes (NTM) are instabilities that can severely degrade the performance and ultimately lead to **disruptions** in a high-β plasma [1].

Electron Cyclotron (EC) waves – microwave beams aimed at the NTM island – can keep the growth under **control** or suppress the NTM.
This operation requires **real-time** tracking of the location of the NTM island, adjusting the beam direction and, possibly, modulating the EC power to match the island rotation.



The Divertor Tokamak Test (DTT) is a (B_T=6 T, I_p=5.5 MA, R_0=2.19 m, a=0.7 m, T_{pulse}=100 s) device [2].

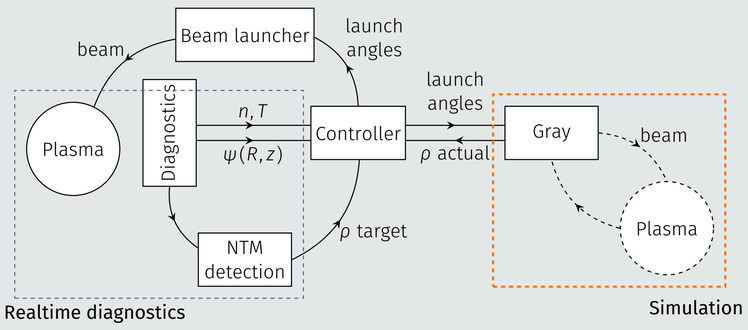


The DTT upper beam launcher used for NTM control

DTT will have **32** 1 MW **EC beams** for heating and current drive (ECRH&CD), with 8 reserved for realtime NTM control.

NTM control system

Open feedback loop principle: realtime diagnostics → **simulation** of the EC beam → steering. **No inline EC emission** (ECE) measurements required.



The NTM controller steers (angle γ) the beam to minimise:

$$\rho_{\text{peak}}(\gamma) - \rho_{\text{target}}$$

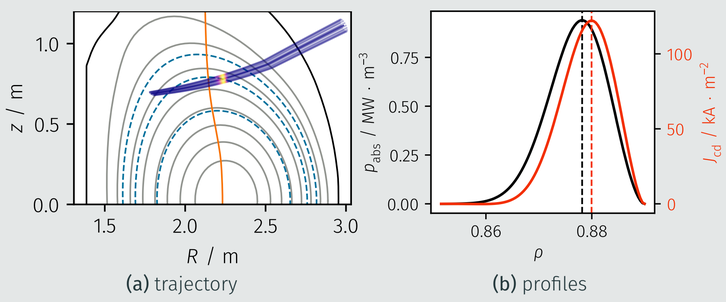
where ρ are minor radii of current peak and target island.

We focus on the **simulation**: developing raytracing software to integrate by adapting the well-known **GRAY**.

GRAY

GRAY is a **beam-tracer** for EC waves in a tokamak [3].

- **Inputs**: MHD equilibrium, kinetic profiles, beam parameters
- **Outputs**: beam trajectory, absorbed **power**, driven **current**



(a) trajectory (b) profiles

Typical outputs for an NTM control setup

Theoretical framework:

- raytracing: quasi optics, **cold plasma** theory
- heating: relativistic **hot plasma** theory
- current drive: **adjoint method**, neoclassical response

GRAY in a nutshell

Complex eikonal ansatz:

$$\mathbf{E}(\mathbf{r},t) = \text{Re}\left[\mathbf{e}(\mathbf{r})e^{iS_R(\mathbf{r})-S_I(\mathbf{r})-i\omega t}\right]$$

Gaussian beam → **N rays** obeying raytracing eqs.:

$$\frac{d\mathbf{r}}{ds} = -\frac{\partial D}{\partial \mathbf{k}}\Big/\left|\frac{\partial D}{\partial \mathbf{k}}\right| \qquad \frac{dS_I}{ds} = 0$$
$$\frac{d\mathbf{k}}{ds} = +\frac{\partial D}{\partial \mathbf{r}}\Big/\left|\frac{\partial D}{\partial \mathbf{r}}\right| \qquad \mathbf{D}(\mathbf{r},\mathbf{k},\omega)\mathbf{E} = 0$$

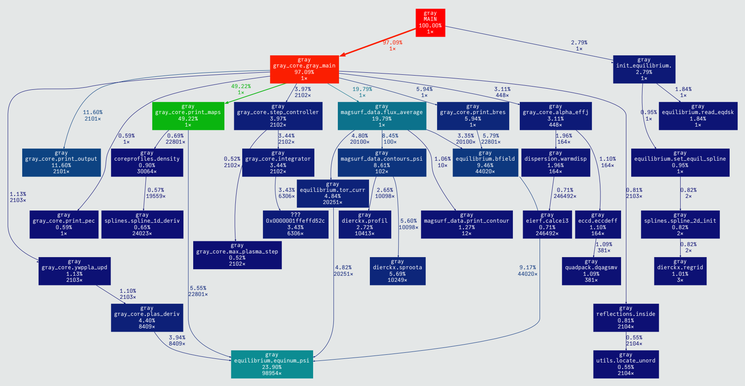
where: $\mathbf{k}=\nabla S_R$ wavevector, s arclength, $D=\det\mathbf{D}(\mathbf{r},\mathbf{k},\omega)$ quasi optical dispersion relation.

1. Integrate the raytracing eqs.
2. At each step:
   - solve hot dispersion relation → absorption coeff. α → power $dP(s) = \alpha P ds$
   - compute current drive efficiency R → current $dI(s) = RdP(s)$
3. Compute $J_{\text{cd}} = dI/dA$ and $p_{\text{abs}} = dP/dV$

Realtime optimisations

Goals for effective NTM control are:

- tracking island evolution (~1 s) ⟶ **execution time of 1-10 ms**
- stabilisation efficiency > 50% ⟶ **max misalignment Δρ = 0.01 (7 mm!)**
- **reliable** when running unsupervised



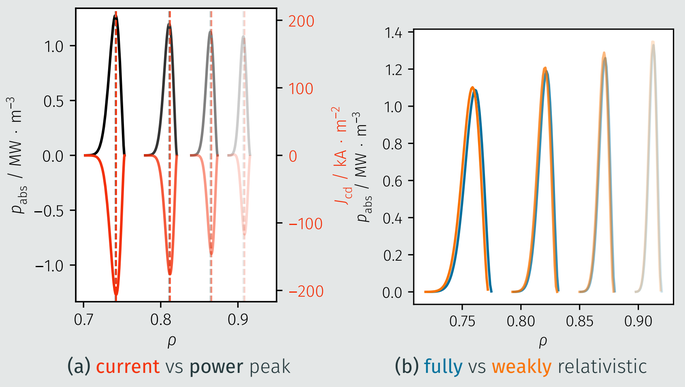
Valgrind [4] callgraph of (unoptimised) GRAY

Profiled the code and **optimised**: 1–2 s ⟶ ~100 ms. For more performance, **approximate**!

- 100% power absorption ⟶ ignore reflections
- single peak profile ⟶ stop when $dP/ds < 0$
- peak $J_{\text{cd}} \approx$ peak p_{abs} ⟶ only compute p_{abs}
- peak unaffected by beam shape ⟶ 1 ray
- weakly relativistic plasma ($kT_e \ll m_e c^2$) [5]

Supported by simulations in DTT **E scenario** [6]:

- plasma: T_e = 20 keV, $n_e = 2.4\times10^{20}$ m^{-3}, B_T = 6 T
- launcher: 170 GHz, ordinary mode, 1° harmonic
- NTM: q = 2 island, $0.7 < \rho_{\text{target}} < 0.9$



(a) current vs power peak (b) fully vs weakly relativistic

Benchmarks

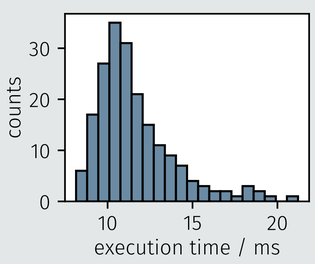
- $\Delta\rho \equiv \rho_{\text{peak, J}} - \rho_{\text{peak, P}}$
- average $\Delta\rho \approx 0.001$
- only **power** → 3x faster!

- $\Delta\rho \equiv \rho_{\text{peak, rel}} - \rho_{\text{peak, weakly}}$
- average $\Delta\rho \approx 0.0001$
- **weakly** 20x faster

Final benchmark: realtime vs full GRAY, 200 simulations

- $\Delta\rho \equiv \rho_{\text{full,J}} - \rho_{\text{realtime,P}}$
- execution time: (11 ± 2) ms
- error: $\Delta\rho = 0.0019(6)$

⟶ **Goals reached!**



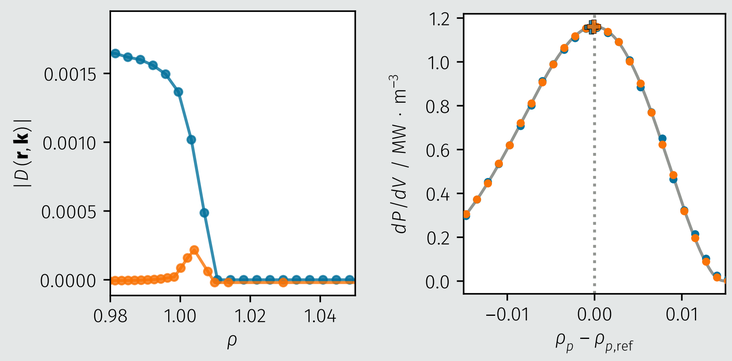
New features

We tested GRAY with **567 simulations** varying: launch position, MHD equilibrium and plasma profiles in a **ramp-up scenario**. We added new feature to **improve robustness**:

1. Adaptive step method estimating the integrator error from the "energy" conservation violation:

$$D(\mathbf{r}_i,\mathbf{k}_i,\omega) = O(h^m),$$

where m is the integrator order, h step size. The step controller adjusts h keeping the **error bounded** and **reducing evaluations** by ~ 2/3!



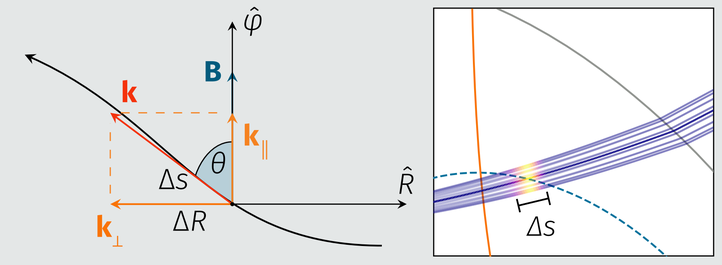
(a) integration error (b) power peak

Comparison of **fixed** vs **adaptive** step methods

2. Max step size based on resonant electron layer thickness; ensures the peak is always resolved.

$$\begin{cases} \gamma(\omega - \mathbf{v}_\parallel\cdot\mathbf{k}) = n\omega_{ce} & \text{EC resonance condition} \\ f(\gamma) \propto \exp(-\mu\gamma) & \text{relativistic electron distr.} \\ B \propto 1/R & \text{magnetic field dependence} \end{cases}$$

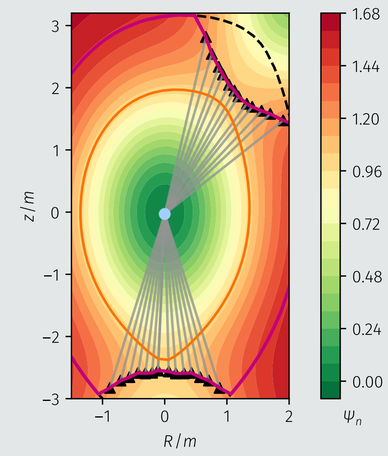
$$\Rightarrow \Delta\gamma \to \Delta R \to \Delta s_{\max}$$



3. Safety domain, to avoid artifacts when mapping density though the flux

$$n(\psi) \to n(R,z) = n(\psi(R,z))$$

outside the separatrix.
Obtained by rescaling the plasma boundary contour excluding regions of decreasing ψ.



Conclusions

We propose an NTM control system for DTT based on raytracing EC waves. We optimised and adapted the GRAY beam-tracer for realtime operation and showed it meets the requirements of speed, accuracy and robustness.

References

[1] R.J. La Haye, Physics of Plasmas. 13 (2006) 55501. https://doi.org/cn8dm8.

[2] S. Garavaglia, et al., Fusion Engineering and Design. 168 (2021) 112678. https://doi.org/gj78rm.

[3] D. Farina, Fusion Science and Technology. 52 (2007) 154–160. https://doi.org/m2ff.

[4] N. Nethercote, J. Seward, in: Proceedings of ACM SIGPLAN 28, ACM, 2007. https://doi.org/b7zr9f.

[5] D. Farina, Fusion Science and Technology. 53 (2008) 130–138. https://doi.org/m2fg.

[6] I. Casiraghi, et Al., Plasma Physics and Controlled Fusion. 65 (2023) 35017. https://doi.org/grx85g.

† m.guerinirocco2@campus.unimib.it